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Computational complexity of bosons in linear networks

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14. ABSTRACT
This project is the first to operating a BOSONSAMPLING device with a bright source of highly-pure single-photon Fock states, using a new kind of solid-state multiphoton source. In detail, the source is emission from an efficient and deterministic quantum dot-micropillar system, demultiplexed into three partially-indistinguishable single-photons, with purity 1g(2)(0) of 0.9900.001 (close to the ideal value of unity), interfering in a 66 linear optics network. Our source is quietlacking higher-order photon terms that introduce noiseallowing the direct exploration of the effect of partial distinguishability in the complexity class of the resulting sampling distribution. Our demultiplexed source is between one and two orders-of-magnitude more efficient than current heralded multiphoton sources based on spontaneous parametric downconversion, allowing us to complete the BOSONSAMPLING experiment far faster than previous equivalent implementations. This intrinsic source superiority places BOSONSAMPLING with larger photon numbers within near reach.

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"Computational complexity of bosons in linear networks"

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Abstract:
A BOSONSAMPLING device is a quantum machine expected to perform tasks intractable for a classical computer, yet requiring minimal non-classical resources as compared to full-scale quantum computers. Theorists have proposed that a BOSONSAMPLING device implemented with as few as 10 photons will be able to outperform a classical machine. Photonic implementations to date employed sources based on inefficient processes—spontaneous parametric downconversion—that only simulate heralded single-photon statistics while strongly reducing emission probabilities: thus leading experimental teams pursuing large-scale BOSONSAMPLING have faced a hard limit of 6 photons. The ideal—BOSONSAMPLING with only single-photon inputs—had thus never been realised before this project.

This project is the first to operating a BOSONSAMPLING device with a bright source of highly-pure single-photon Fock states, using a new kind of *solid-state* multiphoton source. In detail, the source is emission from an efficient and deterministic quantum dot-micropillar system, demultiplexed into three partially-indistinguishable single-photons, with purity $1-g^{(2)}(0)$ of 0.990 ± 0.001 (close to the ideal value of unity), interfering in a 6×6 linear optics network. Our source is quiet—lacking higher-order photon terms that introduce noise—allowing the direct exploration of the effect of partial distinguishability in the complexity class of the resulting sampling distribution. Our demultiplexed source is between one and two orders-of-magnitude more efficient than current heralded multiphoton sources based on spontaneous parametric downconversion, allowing us to complete the BOSONSAMPLING experiment far faster than previous equivalent implementations. This intrinsic source superiority places BOSONSAMPLING with larger photon numbers within near reach.

Introduction:
A core tenet of computer science is the Extended Church-Turing thesis, which states that all computational problems that are efficiently solvable by physically realistic machines are efficiently simulatable with classical resources. In 2011 Aaronson and Arkhipov introduced BOSONSAMPLING, a quantum protocol for efficiently sampling the output of a multimode bosonic interferometer: a problem apparently intractable with classical computation. When scaled to many bosons this model of intermediate—i.e. non-universal—quantum computation will provide the strongest evidence against the Extended Church-Turing thesis.

The most experimentally accessible boson is the photon: to date full BOSONSAMPLING protocols have been performed using up to 4 photons, and protocol validations with up to 6 photons. These initial assays are well short of the numbers of single photons required to probe the Extended Church-Turing thesis: scalable photonic technology is required. The three core technologies needed for scalable quantum photonics are: single-photon sources; large interferometric networks, with current integrated and programmable technology; and efficient photon detection, with demonstrated number resolution, and efficiencies of up to 95%.

To date, BOSONSAMPLING implementations employed photons obtained from spontaneous parametric downconversion, which output is far from ideal single-photon Fock states, n=1, instead producing primarily vacuum with a small admixture of pairs of photons. A non-heralded 2n-photon source can be built by using n downconverters, but it can only be used in specific protocols where the impact of higher photon-numbers is minimised; alternatively, it can be operated as a heralded n-photon source by detecting n photons—one from each downconverter—to herald the presence of their n single-photon partners. Multiphoton rates for state-of-the- art pulsed downconversion sources, pumped at a standard 80 MHz repetition rate, range from ~300 kHz for 2 photons—thus, yielding heralded single-photons at that rate—down to ~3 mHz for 8 photons—accordingly, 4 heralded single-photons at that rate. For as little as 6 heralded single-photons, the rate (~1 per year) becomes less than the detection rate of gravitational waves.

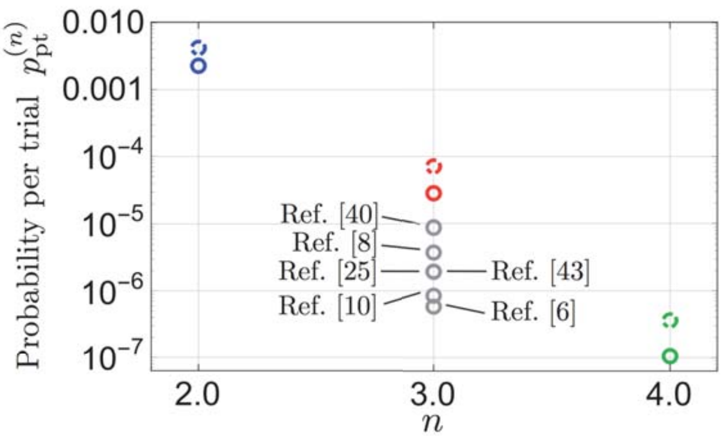

Figure. Multiphoton source efficiency. n-photon probability per trial, *p(n)*, for our n = 2-, 3-, and 4-photon source taken at $1.2P_0$ (solid circles), and at $3P_0$ (dashed circles), where P_0 is the saturation power of 150 µW. The *p(n)* is estimated for various downconversion 3-photon sources (grey circles) employed in previous BOSONSAMPLING experiments. Despite using non-optimised demultiplexing, our 3-photon source is between *one to two orders-of-magnitude* more efficient than the downconversion cases.

Experiment: Please see the attached papers for detailed descriptions of the experiments, theory, equipment and analyses.

Results and Discussion:

We implemented a BOSONSAMPLING device with single-photon Fock states emitted by a highly-efficient, deterministic, quantum dot-micropillar system. A passive temporal-to-spatial demultiplexing scheme—with far from optimal efficiency—resulted in multiphoton sources between one to two orders-of-magnitude *more* efficient than their downconversion versions, which allowed us to complete the BOSONSAMPLING protocol significantly faster than in previous experiments. Implementing the optimal, active, demultiplexing scheme would further boost our multiphoton efficiency *super-exponentially*—with the number of photons—enabling BOSONSAMPLING with larger photon numbers.

Furthermore, we directly observed the effect of partial distinguishability: Our results follow closely the sampling of permanents and immanants of matrices with contributions modulated by photon indistinguishability. Moreover, by exploiting temporal-correlation measurements we showed that both classical and quantum 2-photon sampling distributions can be obtained simultaneously, which can be readily extended to multi-fold temporal-dependent measurements in a larger BOSONSAMPLING experiment. Potentially, this could motivate new validation protocols exploiting statistics that include this temporal degree of freedom.

The impact of partial distinguishability in BOSONSAMPLING has been studied theoretically, and reported experimentally. However, identifying experimentally this property in isolation is challenging.

Previous experiments with downconversion exhibit photon-statistics polluted by higher-order terms, which can be mistakenly interpreted as decreased photon-indistinguishability. In fact, in many cases these higher-order terms, and not photon distinguishability, are the main cause of performance degradation in downconversion-based protocols. The pathway to maximise indistinguishability in efficient solid-state sources is well known: resonant excitation of the quantum-dot results in near-optimal values of photon indistinguishability, in which case the obtained output distributions will be close to the sampling of only permanents—functions belonging to the #P complexity class, in which the main complexity arguments of BOSONSAMPLING apply.

We believe our results pave the way to the forthcoming advent of quantum-dot based quantum photonics, in which a future BOSONSAMPLING implementation with efficiently demultiplexed and resonantly-pumped solid-state sources may finally see the Extended Church-Turing thesis put to serious test.

List of Publications and Significant Collaborations that resulted from your AOARD supported project: In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:
a) papers published in peer-reviewed journals,

1. O. Gazzano, **M. P. Almeida**, A. K. Nowak, S. L. Portalupi, A. Lemaître, I. Sagnes, **A. G. White**, and P. Senellart
   Entangling Quantum-Logic Gate Operated with an Ultrabright Semiconductor Single-Photon Source
   Physical Review Letters **110**, 250501 (2013) —Published 17 June 2013
   doi:10.1103/PhysRevLett.110.250501

2. N. Somaschi, V. Giesz, L. De Santis, J. C. Loredo, **M. P. Almeida**, G. Hornecker, S. L. Portalupi, T. Grange, C. Antón, J. Demory, C. Gómez, I. Sagnes, N. D. Lanzillotti-Kimura, A. Lemaítre, A. Auffeves, **A. G. White**, L. Lanco and P. Senellart
   Near-optimal single-photon sources in the solid state
   Nature Photonics **10**, 340–345 (2016) —Published online 07 March 2016
   doi:10.1038/nphoton.2016.23

3. J. C. Loredo, N. A. Zakaria, N. Somaschi, C. Anton, L. de Santis, V. Giesz, T. Grange, M. A. Broome, O. Gazzano, G. Coppola, I. Sagnes, A. Lemaitre, A. Auffeves, P. Senellart, **M. P. Almeida**, and **A G. White**
   Scalable performance in solid-state single-photon sources
   Optica **3**, 433-440 (2016) —Published online 13 April 2016
   doi:10.1364/OPTICA.3.000433

b) papers published in peer-reviewed conference proceedings,
None.

c) papers published in non-peer-reviewed journals and conference proceedings,
None.

d) conference presentations without papers,
The full details of each conference can be found at: http://quantum.technology/conf

2013 4/18 SPIE, Prague	White, Experimental BOSONSAMPLING
2013 6/16 CQO X - QIM 2, Rochester	White, Experimental BOSONSAMPLING
2013 7/11 CLEO2013 San Jose	Broome, BOSONSAMPLING
2013 7/13 IEEE 2013 Hawaii	Broome, BOSONSAMPLING
2013 7/29 FQMT13 Prague	White, Experimental BOSONSAMPLING
2013 8/16 IWQI, Paraty	White, Experimental BOSONSAMPLING
2013 10/2 Benasque	White, Photonic Quantum Simulation & Emulation
2013 11/05 NTT, Tokyo	White, Photonic Quantum Simulation & Emulation
2014 2/11, Quantum Simulation, Bad Honnef	White, Photonic Quantum Simulation & Emulation
2014 3/20, QIM 2014, Berlin	White, Photonic Quantum Simulation
2014 5/23, Quantum14, Turin	White, Photonic Quantum Simulation
2014 7/09, ACOFT, Melbourne	White, Photonic Quantum Simulation
2014 8/04, ICAP, Washington DC	White, Photonic Quantum Simulation
2015 5/6 Shanghai *	White, Photonic Quantum Simulation & Emulation
2015 6/22 QUROPE Summer School, Hindås	White, Photonic Quantum Information
2015 10/19, FiO 2015, San Jose	White, Photonic Quantum Simulation & Emulation
2015 11/23 Many-body physics with light, Santa Barbara	White, Photonic Quantum Simulation & Emulation

* The 2015 Shanghai meeting was a "Multiphoton Interferometry Workshop", focussed on BOSONSAMPLING and its implications. White gave the Introductory Keynote.

e) manuscripts submitted but not yet published, and

4. J. C. Loredo, **M. A. Broome**, P. Hilaire, O. Gazzano, I. Sagnes, A. Lemaitre, **M. P. Almeida**, P. Senellart, and **A. G. White**
   BOSONSAMPLING with single-photon Fock states from a bright solid-state source
   arXiv:1603.00054 (2016) —Published online 29 February 2016

5. L. de Santis, C. Antón, B. Reznychenko, N. Somaschi, G. Coppola, J. Senellart, C. Gómez, A. Lemaître, I. Sagnes, **A. G. White**, L. Lanco, A. Auffeves, and P. Senellart
   A solid-state single-photon filter
   arXiv:1607.05977 (2016) —Published online 20 July 2016

f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

This work significantly enhanced and deepened the collaboration with Professor Pascale Senellart and her team at:

Groupe d'Optique des Structures Semi-conductrices
Centre de Nanosciences et de Nanotechnologies
Centre National de la Recherche Scientifique, France
&
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